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**THE EFFECT OF PREHEAT TEMPERATURE AND  
INTER-PASS REHEATING ON MICROSTRUCTURE AND  
TEXTURE EVOLUTION DURING HOT ROLLING OF  
Ti-6Al-4V (PREPRINT)**

**A.A. Salem, M.G. Glavicic, and S.L. Semiatin**

**Metals Branch**

**Metals, Ceramics, and NDE Division**

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# **The Effect of Preheat Temperature and Inter-Pass Reheating on Microstructure and Texture Evolution during Hot Rolling of Ti-6Al-4V**

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## **Abstract**

The effect of preheat temperature and inter-pass reheating on microstructure and texture evolution during unidirectional hot rolling of Ti-6Al-4V in the alpha + beta field was investigated. Three different heating schedules were used to roll plates at 10 pct. reduction per pass to a 3:1 total reduction (true strain = 1.15): (1) preheat at 955°C with inter-pass reheating for 3 minutes, (2) preheat at 955°C without inter-pass reheating, and (3) preheat at 815°C with inter-pass reheating for 3 minutes. Following rolling, each plate was air cooled to simulate production practice. The microstructures and textures were determined using electron-backscatter and X-ray diffraction techniques. The results revealed that the intensity of basal poles decreased along the rolling direction and increased along the normal and transverse directions with decreasing rolling (furnace) temperature or the elimination of reheating between passes.

*Keywords:* Ti-6Al-4V alloy, hot rolling, texture, reheating

## **1. Introduction**

Alpha/beta titanium alloys provide an excellent combination of high strength, corrosion resistance, and low density. Hence, they are widely used for many applications, especially in the aerospace industry. Accounting for approximately 80 pct. of the total usage in the US market [1], Ti-6Al-4V is the most common material in this class. The mechanical behavior of the material

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can be tailored by altering microstructure and texture through judicious choice of thermomechanical processing (TMP) parameters [2-4].

In general, three broad types of microstructures can be developed in alpha/beta titanium alloys by TMP [2-4], namely, fully lamellar, fully equiaxed, and duplex (bi-modal). A mixture of equiaxed particles of primary alpha ( $\alpha_p$ ) and lamellae of secondary alpha ( $\alpha_s$ ) in a matrix of beta ( $\beta$ ) phase comprises the duplex microstructure. Numerous applications require the duplex microstructure due to its good yield strength and ductility, fatigue-crack-initiation resistance, and slow fatigue-crack-propagation rate [5].

The duplex microstructure can exhibit moderate-to-strong crystallographic textures that develop during large deformation in the alpha + beta phase field. For example, unidirectional rolling usually gives rise to two major types of textures: the so-called basal/transverse (B/T), in which the alpha-phase basal poles are located along the plate-normal and long-transverse directions, and transverse (T) [3]. Low temperature deformation tends to result in the B/T texture while high temperature deformation (close to the beta transus at which alpha + beta  $\rightarrow$  alpha) results in the T texture.

Previous research for titanium alloys with a duplex microstructure has focused for the most part on the overall texture of the alpha phase, without separating that of the  $\alpha_p$  and  $\alpha_s$  micro-constituents. However, the textures of  $\alpha_p$  and  $\alpha_s$  evolve primarily as a result of either the deformation in the two-phase field or the decomposition of the hot-worked beta matrix during cooling, respectively. Thus  $\alpha_p$  and  $\alpha_s$  may be expected to develop different texture components during TMP.

The separation of the  $\alpha_p$  deformation texture and the  $\alpha_s$  transformation texture is complicated by the fact that the alpha phase in each instance consists of the same crystal structure and lattice parameters. Consequently, it is very difficult to distinguish between them using standard measurements techniques based on x-ray or electron-backscatter diffraction (XRD, EBSD) [6]. Because the morphology and texture of  $\alpha_p$  particles and  $\alpha_s$  lamellae each have a major influence on final mechanical properties, a number of techniques are now under development to meet this need [6].

The current work was undertaken as part of a larger program to apply advanced characterization techniques to quantify the effect of TMP parameters on the evolution of microstructure and texture in alpha/beta titanium alloys such as Ti-6Al-4V. The specific objective of the present effort was to establish the effect of rolling temperature and reheat schedule on microstructure and texture development. For this purpose, techniques based on simultaneous EBSD and EDS (electron-dispersive spectroscopy) or EBSD image-quality maps were used to separate the textures of primary and secondary alpha [6].

## **2. Material and experimental procedures**

### *2.1. Material*

The material used in the present program was identical to that employed previously [6]. It comprised Ti-6Al-4V which was received as 32-mm-thick plate having a measured composition (in weight pct.) of 6.15 aluminum, 3.9 vanadium, 0.20 oxygen, 0.21 iron, 0.008 nitrogen, 0.01 carbon, 0.0031 hydrogen, and balance titanium. The beta transus temperature was 1080°C.

The as-received Ti-6Al-4V material was heated to 955°C, thus dissolving all  $\alpha_s$  lamellae from prior processing, soaked for four hours, and furnace cooled to produce a microstructure of ~95 pct. equiaxed-alpha particles ( $\alpha_p$ ) in a matrix of retained beta. Selected samples were water

quenched from 955°C in order to quantify the texture (and microstructure) of the primary alpha present at the soak temperature.

## *2.2. Experimental procedures*

The broad effect of TMP parameters on microstructure and texture development was determined by conventional hot rolling of samples measuring 32 x 38 x 76 mm that were cut from the heat-treated-and-furnace-cooled material. The preform width (38 mm) was limited by the load capacity of the two-high rolling mill that was used. Each preform was furnace heated to a temperature of either 815 or 955°C, soaked for 40 minutes, and hot rolled at a speed of 30 m/min to a 3:1 total reduction using a 10-pct. reduction per pass and a reheat time between passes of three minutes. To provide further insight into the effect of heating schedule on texture and microstructure development, an additional perform was rolled in a similar fashion using a furnace (preheat) temperature 955°C but without inter-pass reheating. Each of the final plates was air cooled following rolling to mimic industrial practice.

To characterize microstructure and texture, samples of the unrolled material and the hot-rolled plates were sectioned along the mid-plane, ground, and electropolished at 20°C in a solution of 590 ml methanol and 60 ml perchloric acid. Following electropolishing, each sample was mounted on the tilting stage inside an XL30 field-emission-gun scanning-electron-microscope (FEG-SEM). The microscope was operated at 20 kV and 10 nA with the stage tilted at an inclination of 70°.

Kikuchi patterns were collected using an EBSD system from EDAX [7]. In addition, the local composition was determined via simultaneous EDS analysis. A 0.3- $\mu\text{m}$  step size was used to cover an area measuring 80  $\mu\text{m}$  x 120  $\mu\text{m}$ . Different step sizes and larger areas (within the maximum of 25 mm x 35 mm associated with the microscope construction) were also utilized.

The textures of  $\alpha_p$  and  $\alpha_s$  were separated using the EBSD/EDS technique described in Reference 6.

The texture results from the present technique were compared to those obtained using the x-ray-diffraction (XRD) approach developed previously by Glavicic, *et al.* [8]. For this purpose, an additional sample was removed from each of the hot-rolled Ti-6Al-4V plates. Each of these pieces was then cut into two equal sections. One half was analyzed in the as-hot-rolled condition. The other was given a heat treatment to produce an alpha microstructure that was fully globular; i.e., it was annealed at 960°C (just above the rolling temperature) for one hour followed by furnace cooling. The volume fraction of primary alpha in the as-hot-rolled duplex microstructure was determined by analysis of backscattered electron (BSE) images taken in a Leica-Cambridge Stereoscan 360 FEG-SEM. Subsequently, both pieces were prepared for XRD on the RD-TD plane at the mid-thickness of the rolled plate using standard metallographic techniques. XRD measurements were conducted using Cu K $\alpha$  radiation from an 18 kW rotating anode source, and textures were determined from measurements of partial  $(10\bar{1}0)$ ,  $(0002)$ ,  $(10\bar{1}1)$ ,  $(10\bar{2}1)$ , and  $(11\bar{2}0)$  alpha-phase pole figures. In addition, partial  $(110)$  and  $(200)$  beta-phase pole figures were determined to enable a comparison of the  $\alpha_s$  texture and the texture of the parent beta phase. The partial pole figures were completed using the orientation-distribution-function (ODF) software in popLA (preferred orientation package from Los Alamos National Laboratory) [9].

### 3. Results and discussion

Microstructure and texture results demonstrated a marked dependence on rolling temperature primarily due to the associated variation in the volume fractions of the alpha and beta phases. The volume fraction of alpha is ~0.70 at 815°C and ~0.3 at 955°C [10]. These differences affect the relative partitioning of strain between the two phases and thus the evolution

of deformation texture as well as the development of the secondary-alpha texture due to decomposition of the hot-worked beta matrix.

### *3.1. Microstructure evolution*

BSE micrographs revealed a noticeable dependence of microstructure on processing variables. The microstructure of the starting material heated 4 h at 955°C and water quenched (Figure 1a) contained 30 pct.  $\alpha_p$  in a matrix of fine martensitic alpha in agreement with the results for Ti-6Al-4V in Reference 10. By contrast, furnace cooling following the heat treatment at 955°C produced ~93 pct. equiaxed alpha in a matrix of retained beta (Figure 1b). The absence of any transformation product in the furnace-cooled sample confirmed the appropriateness of the heat treatment to dissolve all secondary-alpha lamellae in the as-received material, and therefore assured that the measured secondary-alpha textures were due solely due to the prescribed TMP practices.

BSE micrographs of the hot-rolled materials (Figure 2) mirrored their respective processing parameters, denoted here as HTWR (rolled from a furnace at 955°C with inter-pass reheats), HTNR (rolled from a furnace at 955°C without inter-pass reheats), and LTWR (rolled from a furnace at 815°C with inter-pass reheats). Routes HTWR and HTNR both showed a duplex microstructure with a mixture of  $\alpha_p$  and  $\alpha_s$  lamellar colonies. Specifically, the volume fractions of  $\alpha_p$  were 0.30 and 0.30 for the HTWR and HTNR routes, respectively. The similarity of the volume fraction of  $\alpha_p$  in the HTWR sample to that in the sample water quenched from 955°C suggested that the cooling rate after the final pass was fast enough to prevent substantial growth of the  $\alpha_p$  prior to the decomposition of the beta matrix. Similarly, measurements of the surface temperature and rolling pressure at the completion of the HTNR sequence indicated that the temperature within this perform had dropped to ~815°C during transfer from the furnace and



the various rolling passes prior to final air cooling. In this case, the lack of a large amount of growth of  $\alpha_p$  may be ascribed to the rapid decomposition of the beta matrix due to concurrent deformation, thus providing a strong pinning tendency and reducing the supersaturation required for growth of  $\alpha_p$ .

Compared to the observations for samples rolled using a furnace temperature of 955°C, the microstructure for route LTWR did not show any signs of  $\alpha_s$  lamellae and a volume fraction of  $\alpha_p$  comparable to that at the rolling temperature, i.e., 0.68 for the rolled sample versus 0.70 for the preheated-and-water-quenched material.

### *3.2. Texture evolution*

Texture evolution during preheating and after the three different rolling processes was quantified using (0001) alpha-phase pole figures for  $\alpha_p + \alpha_s$ , for  $\alpha_p$  by itself, and for  $\alpha_s$  by itself. Selected beta-phase textures were also determined and represented using (110) pole figures.

#### *3.2.1. Combined $\alpha_p + \alpha_s$ textures*

The combined texture of the primary and secondary alpha ( $\alpha_p + \alpha_s$ ) revealed a noticeable dependence on processing parameters. For the unrolled material, furnace cooling from 955°C produced a strong texture comprising basal poles along the rolling and transverse directions (RD and TD) with almost similar intensity. Water quenching led to a major texture component along the RD only (Figure 3).

The intensity and nature of the texture components was greatly reduced by rolling (Figure 4). Specifically, the times-random intensities were reduced from ~15 to ~4. Furthermore, the intensity along the TD was greater and the intensity along the RD lesser for the lower rolling temperature (i.e., 815°C) with reheats (Figure 4d) compared to the intensities for the sample

rolled at 955°C with reheats (Figures 4b). Moreover, a new component appeared with the c-axis titled  $\sim 20^\circ$  from the ND towards the RD for the sample rolled at 815°C. Rolling from a 955°C furnace *without* reheating had a similar but weaker effect on the texture components compared to the observations for low-temperature rolling. That is to say, there was a measurably greater intensity of basal poles along the TD and a component with the c-axis titled from the ND towards the RD (Figure 4c).

The measured textures contrast somewhat with results in literature [2-4, 11], an effect that may be ascribed to differences in starting microstructure and texture as well as reheating practices. In particular, the work by and Peters and Luetjering [4] utilized Ti-6Al-4V with a random starting texture and a transformed beta microstructure; rolling was done without reheating. A B/T-type texture was obtained at low rolling temperatures at which a high volume fraction of alpha is present during deformation. At temperatures high in the alpha + beta phase field, at which the volume fraction of beta is large, a *beta* deformation texture was developed during rolling. To rationalize the T texture of the *alpha* phase formed during cooling from these temperatures, therefore, Peters and Luetjering concluded that preferential variant selection occurred during decomposition of the beta; i.e., during the cooling process, alpha phase formed on only one of the six possible  $\{110\}$  planes of the beta phase that satisfy the Burgers relationship  $(0002)_\alpha \parallel (110)_\beta$ . [12]. According to Frederick [13], the favored variant(s) are controlled by the strain imposed during the rolling process. Last, for samples rolled at *intermediate* temperatures in the two-phase field, the intensity of the alpha-phase deformation texture (B/T) would tend to decrease because of partial alpha-phase accommodation of the imposed strain, and the T texture associated with beta transformation would be of low intensity

due to the moderate volume fraction of beta present during deformation [13]. Consequently, a fairly weak overall alpha-phase texture is observed at intermediate rolling temperatures [4].

In contrast to the work of Peters and Luetjering [4], the *starting* texture was not random for the present material. It had basal poles along both the RD and TD. Because high temperature rolling tends to produce the T type texture, the intensity of the texture component along the TD in the present material would tend to predominate relative to the one along the RD for rolling at 955°C with reheats, as was observed (Figure 4b). Reheating between passes in the present work may have tended to lessen the tendency to form a sharp beta deformation texture (and the associated alpha texture developed during transformation) due to static recrystallization and thus explain the low overall texture intensity formed during rolling at 955°C compared to that found by Peters and Luetjering [4].

Because deformation at low temperatures tends to yield a B/T type (deformation) texture, rolling at 815°C in the present work would tend to weaken the intensity of the basal poles along the RD and strength the ones along the TD, as was observed (Figure 4d). In addition, a component comprising basal poles along the normal direction (ND) would develop, in line with the appearance of the component titled ~20° from the ND.

Hot rolling from a furnace at 955°C without reheating between passes represents a scenario combining features of the other two sequences. During the initial passes, the T type texture would be dominant, while at the end of the rolling the development of the B/T type of texture would be promoted. The net result was a high intensity of basal poles along the TD and a weaker intensity of the B-type texture compared to rolling at 815°C with reheats (Figure 4c).

### 3.2.2. Primary-alpha ( $\alpha_p$ ) textures

Separation of the primary-alpha ( $\alpha_p$ ) texture from the overall alpha-phase texture using the EBSD/EDS and EBSD/image-quality techniques provided further insight into the effect of rolling temperature and reheating on texture formation.

For the sample rolled at 955°C with inter-pass reheating, for example, EBSD/EDS separation revealed that a majority of the basal poles in the  $\alpha_p$  texture were aligned with the RD (Figure 5a), in contrast to the slight predominance of the TD component for the overall texture (Figure 4b). Moreover, the  $\alpha_p$  texture was seen to be much stronger after separation from the weak overall texture developed during rolling at 955°C (Figure 4b). A masking effect of the  $\alpha_p$  texture by the overall texture can be ascribed to the small volume fraction of primary alpha at 955°C. Furthermore, there was no evidence of texture components lying at 45° to the RD (and TD) (i.e.,  $\gamma$  fiber) in the  $\alpha_p$  texture following rolling at 955°C, in contrast to the observation for the unrolled-and-furnace-cooled material (Figure 4a/3b.).

Further examination of the texture of the unrolled material which was annealed at 955°C and then water quenched (Figure 3a) provided a plausible explanation for the strong  $\alpha_p$  RD component following rolling at 955°C. Because of the poor image quality of the martensitic alpha, the pole figure in Figure 3a pertains to the *primary alpha* at 955°C. A comparison of Figures 3a and 5a thus reveals that the  $\alpha_p$  texture after rolling at 955°C was largely inherited from the starting  $\alpha_p$  texture. The small amount of plastic strain accommodated by the low volume fraction of primary alpha during rolling at 955°C led to a slight “smearing” and rotation of the basal poles toward the TD direction, but not enough to noticeably eliminate the very strong RD component inherited from the unrolled material.

During high-temperature rolling without reheating, the temperature of the material dropped considerably toward the end of the rolling process. Although the volume fraction of

primary alpha did not change noticeably (Figure 2b), beta matrix decomposition occurred *during* rolling, leading to a microstructure of primary alpha in a much stiffer transformed beta matrix. This microstructure increased the amount of plastic strain accommodated by  $\alpha_p$  (relative to that during rolling at 955°C with inter-pass reheating) and enhanced the formation in the  $\alpha_p$  of a marked deformation texture comprising a strengthened texture component along the TD and the appearance of basal poles close to the ND (Figure 5b). Similarly, rolling at 815°C, at which the microstructure comprised a large amount of primary alpha and a small amount of beta, led to an increase in the intensity of the TD component, the disappearance of the RD component, and the appearance of the B-type texture for the  $\alpha_p$  portion of the material (Figure 5c). These results confirm that the deformation of primary alpha contributes greatly to the formation of the B/T-type texture.

### 3.2.3. Secondary alpha texture

The  $\alpha_s$  textures separated from the overall texture using the EBSD/EDS technique shed further light on deformation during rolling with a preheat (furnace) temperature of 955°C. During rolling at 955°C with inter-pass reheating, most of the plastic strain is accommodated by the soft beta phase, and a strong deformation texture is formed in the beta. When the confounding influence of the primary alpha (and its associated RD texture component) is subtracted from the overall texture, the degree of variant selection during decomposition of the hot-worked beta became apparent (Figure 6a). Not surprisingly, the TD component was strongest in agreement with the work of Frederick [13]. However, additional weaker components along the RD and at 45° to the RD and TD, which are also related to the beta deformation texture, were evident.

The relationship between the  $\alpha_s$  texture developed by hot rolling at 955°C with inter-pass reheating and the corresponding beta-deformation texture was further elucidated by a comparison of the basal pole figure for the  $\alpha_s$  (figure 6a) and the (110) pole figure for the beta (Figure 7a). The beta texture was a classical “cube-on-face” type, i.e., (100)<011>. The correspondence of the locations of the intensity maxima on the two figures is evident, thus indicating that the burgers relation was obeyed for the close-packed planes in the beta and alpha phases during decomposition of the former. However, the comparison does show quantitative differences in the intensities at specific locations. The (110) $_{\beta}$  pole figure showed an essentially uniform intensity for all its texture components. On the other hand, the (0001) $_{\alpha}$  pole figure showed a stronger intensity along the TD and weaker intensities at the other locations. This difference in intensities can be explained by preferential variant selection during the beta-to-alpha transformation, for if all twelve variants of alpha phase were to occur with equal probability, the (101) $_{\beta}$  pole figure would be similar to the (0001) $_{\alpha}$  pole figure [14], which was not the case.

For hot rolling at 955°C without inter-pass reheats, part of the beta matrix decomposed to form  $\alpha_s$  lamellae as the temperature dropped continuously during deformation and between passes. The deformation and transformation behavior therefore led to two distinct differences in the nature of texture evolution in comparison to the case involving reheating between passes. First, as noted in Section 3.2.2, the strain partitioned to the primary alpha was increased, thereby enhancing the formation of deformation texture in this constituent. Secondly, the beta deformation texture prior to transformation would have been sharper and the dislocation substructure developed in the beta phase would have been higher in samples rolled without reheating due to the reduced recovery rates at lower temperatures, let alone the absence of the

reheating soak times. The very sharp  $\alpha_s$  texture (Figure 6b) may thus be related to the sharp beta deformation texture as well as a possible enhancement of the variant selection process associated with dislocation substructure.

Samples rolled at 815°C did not have a measurable amount of  $\alpha_s$  (Figure 3c).

### *3.3. Comparison of EBSD and XRD techniques*

The overall textures determined by the “indirect” XRD technique (Figure 8) were similar to those derived via EBSD (Figure 4); i.e., they showed an increase in the intensity along the TD, a weakening of the intensity along the RD, and the appearance of tilted ND basal poles as the rolling temperature was decreased. Although both techniques involved sampling of equivalent areas (25 x 25 mm), however, there were some distinctive differences in the measurements, especially for the unrolled material and the sample rolled at 955°C with inter-pass reheating (Figure 4a,b and Figure 8a,b). For example, XRD showed an extra texture component at 45° from the RD and TD (Figures 4a vs. 8a). This component was most probably due to overlap of the alpha and beta peaks in the XRD patterns.

The XRD  $\alpha_p$  textures (Figure 9), utilizing samples heated to the prior TMP temperature and furnace cooled to eliminate secondary alpha, were also similar, but not identical, to the corresponding EBSD/EDS data measured directly on samples containing both primary and secondary alpha (Figure 5). The XRD measurements revealed that rolling at lower temperatures caused an increase in the intensity of the TD component and a weakening of the RD component until it disappeared completely during rolling at 815°C, in broad agreement with the EBSD/EDS results. As surmised previously [6], some of the quantitative differences between the results from the two methods are a result of the preferential enhancement of selected texture components

during the heat treatment used to grow the primary alpha for the XRD method. Contamination of the  $(0001)_\alpha$  pole figures with  $(101)_\beta$  peaks (e.g., Figure 9a) may have led to some of the differences as well.

The XRD  $\alpha_s$ -texture component calculated by subtraction of the  $\alpha_p$  texture from the overall texture [8] (Figure 10) exhibited moderate basal-pole intensities along the TD that were similar to but lower in magnitude than those from the EBSD/EDS method (Figure 6). However, the weaker RD components were not detected by XRD. Hence, it is concluded that the XRD texture separation technique may yield results which are beneficial for overall process design but should not be viewed as being totally quantitative.

#### **4. Summary and conclusions**

Samples of Ti-6Al-4V with an equiaxed-alpha preform microstructure were rolled with and without inter-pass reheating at high and low temperatures in the alpha + beta phase field. From this work, the following conclusions were drawn:

1. Irrespective of rolling temperature, the alpha-phase texture includes a component comprising basal poles along the TD. For high temperature rolling with inter-pass reheating, this is the main component and results from the formation of secondary alpha via non-random variant selection during the decomposition of the beta matrix.
2. High temperature hot rolling without reheating results in basal/transverse-type deformation texture with a weak basal component. The strength of the basal component increases by decreasing the rolling temperature.
3. Both primary and secondary alpha contribute to the basal/transverse type texture during low temperature rolling.



4. The presence of RD texture components following hot rolling may be associated with the persistence of a primary-alpha component present in the material prior to rolling.

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### **Figure Captions**

Figure 1. SEM BSE images of the microstructure developed in the *unrolled* Ti-6Al-4V program material during heat treatment at 955°C for 4 hours followed by (a) water quenching or (b) furnace cooling.

Figure 2. SEM BSE images of the microstructures developed in Ti-6Al-4V during air cooling following rolling at (a) 955°C with 3-min inter-pass reheats, (b) 955°C with no reheating, and (c) 815°C with 3-min inter-pass reheats. The rolling direction (RD) is horizontal, and the long transverse direction (TD) is vertical.

Figure 3. Alpha-phase (0001) pole figures determined by EBSD for unrolled Ti-6Al-4V heat treated 4 hours at 955°C followed by (a) water quenching or (b) furnace cooling. Scanned areas were 1.2 mm x 1.2 mm. (Mention that figure (a) comprises only primary alpha)

Figure 4. Alpha-phase ( $\alpha_p + \alpha_s$ ) {0001} pole figures determined by EBSD for Ti 6Al-4V (a) as-heat-treated and furnace cooled, Rolled along the Reference direction at (b) 955°C + 3 min reheat, (c) 955°C + No reheat, and (d) 815°C + 3 min reheat and rolled perpendicular to the reference direction (e) 955°C + 3 min reheat and (f) 815°C + 3 min reheat.

Figure 5. Primary-alpha ( $\alpha_p$ ) (0001) pole figures determined by EBSD/EDS for Ti-6Al-4V rolled at (a) 955°C with 3-min inter-pass reheats, (b) 955°C with no reheating, and (c) 815°C with 3-min inter-pass reheats.

Figure 6. Secondary-alpha ( $\alpha_s$ ) (0001) pole figures determined by EBSD/EDS for Ti-6Al-4V rolled at (a) 955°C with 3-min inter-pass reheats and (b) 955°C without inter-pass

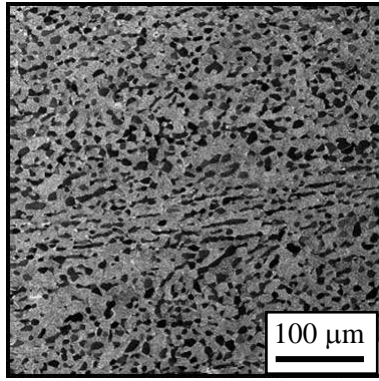
reheats. The material rolled at 815°C with inter-pass reheating did not contain measurable secondary alpha.

Figure 7. Comparison of (a)  $(110)_\beta$  pole figure determined by XRD and (b) the  $(0001)_\alpha$  secondary-alpha pole figure determined by EBSD/EDS for Ti-6Al-4V after hot rolling at 955°C with 3-min inter-pass reheats.

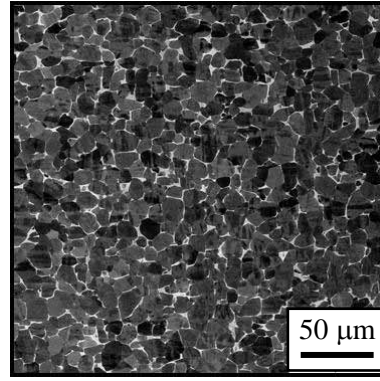
Figure 8. Alpha-phase ( $\alpha_p + \alpha_s$ ) (0001) pole figures determined by XRD for Ti-6Al-4V (a) heat treated and furnace cooled, (b) rolled at 955°C with 3-min inter-pass reheats, (c) rolled at 955°C with no reheating, and (d) rolled at 815°C with 3-min inter-pass reheats.

Figure 9. Primary-alpha ( $\alpha_p$ ) (0001) pole figures determined by XRD for Ti-6Al-4V rolled at (a) 955°C with 3-min inter-pass reheats, (b) 955°C with no reheating, and (c) 815°C with 3-min inter-pass reheats.

Figure 10. Secondary-alpha ( $\alpha_s$ ) (0001) pole figures determined by the XRD texture subtraction technique [8] for Ti-6Al-4V rolled at (a) 955°C with 3-min inter-pass reheats and (b) 955°C without inter-pass reheats. The material rolled at 815°C with inter-pass reheating did not contain measurable secondary alpha.

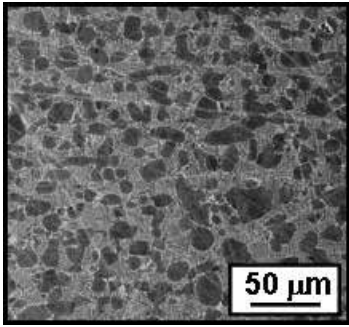


(a)

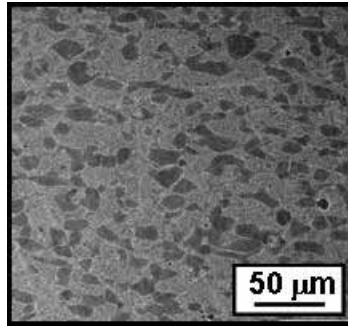


(b)

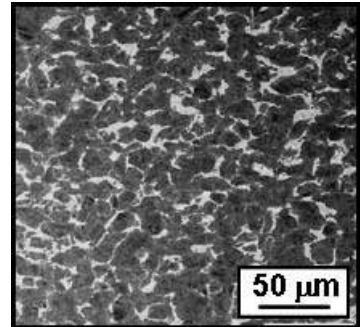
Figure 1. SEM BSE images of the microstructure developed in the *unrolled* Ti-6Al-4V program material during heat treatment at 955°C for 4 hours followed by (a) water quenching or (b) furnace cooling.



(a)



(b)



(c)

Figure 2. SEM BSE images of the microstructure developed in the Ti-6Al-4V program material *as-rolled* and air cooled at (a) 955°C + 3 min reheat, (b) 955°C + No reheat, and (c) 815°C + 3 min reheat. The rolling direction (RD) is horizontal and transverse direction (TD) is vertical.

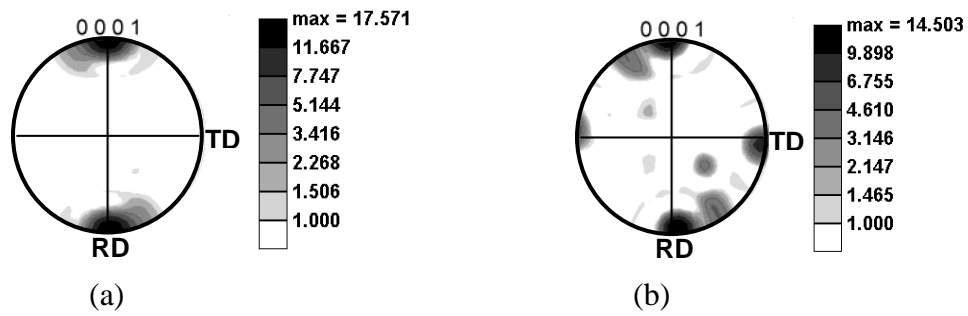


Figure 3. Alpha-phase (0001) pole figures determined by EBSD for *unrolled* Ti-6Al-4V heat treated 4 hours at 955°C followed by (a) water quenching or (b) furnace cooling. Scanned areas were 1.2 mm x 1.2 mm.

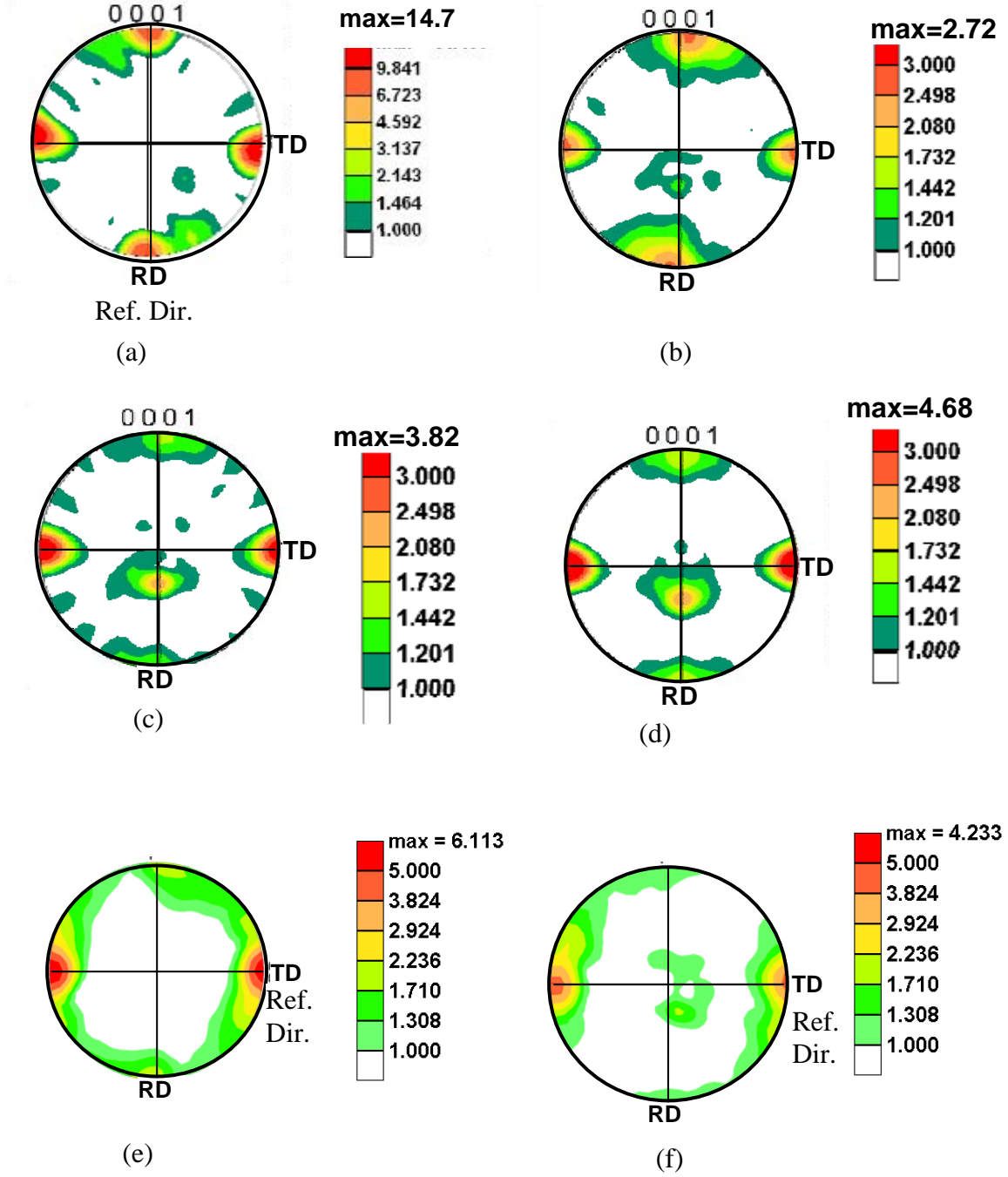


Figure 4. Alpha-phase ( $\alpha_p + \alpha_s$ ) {0001} pole figures determined by EBSD for Ti 6Al-4V (a) as-heat-treated and furnace cooled, Rolled along the Reference direction at (b) 955°C + 3 min reheat, (c) 955°C + No reheat, and (d) 815°C + 3 min reheat and rolled perpendicular to the reference direction (e) 955°C + 3 min reheat and (f) 815°C + 3 min reheat.

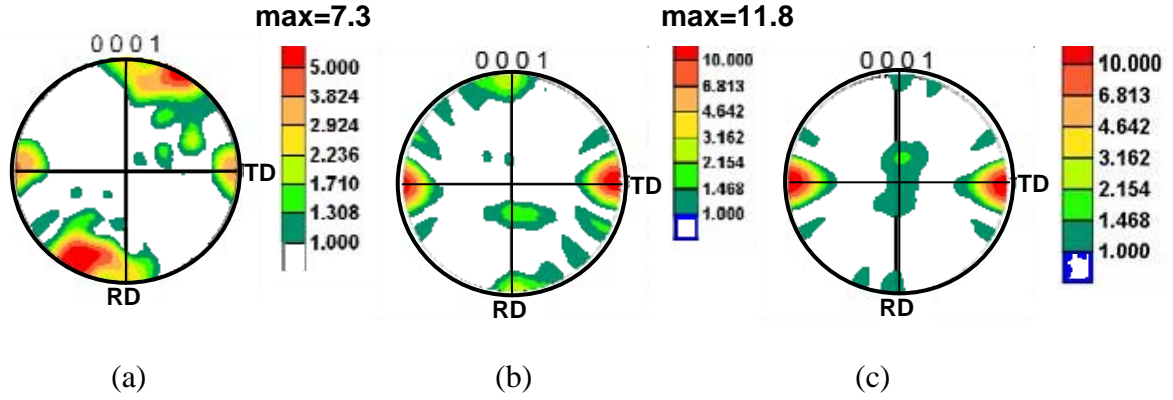


Figure 5. Primary Alpha-phase ( $\alpha_p$ ) {0001} pole figures determined by EBSD/EDS for Ti 6Al-4V (a) rolled at 955°C with 3 min reheat, (b) rolled at 955°C without reheat, and (c) rolled at 815°C with 3 min reheat.

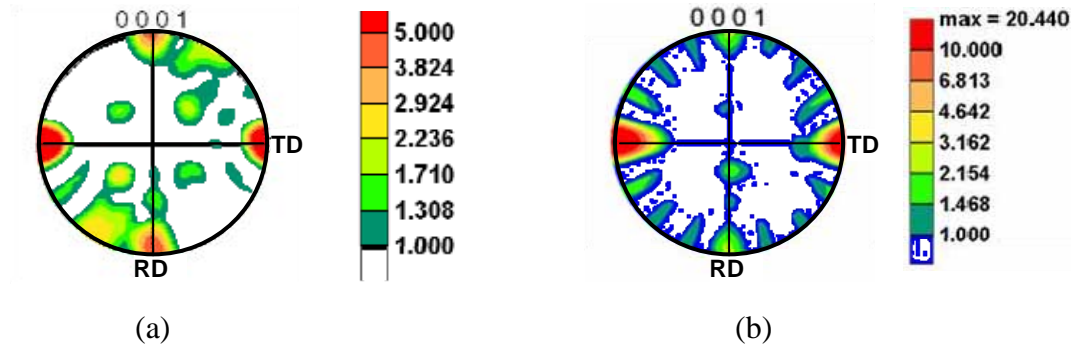


Figure 6. Secondary alpha-phase ( $\alpha_s$ ) {0001} pole figures determined by EBSD/EDS for Ti 6Al-4V (a) rolled at 955°C with 3 min reheat and (b) rolled at 955°C without reheat. Note, that the material rolled at 815°C with reheat did not have secondary alpha (figure 3c).

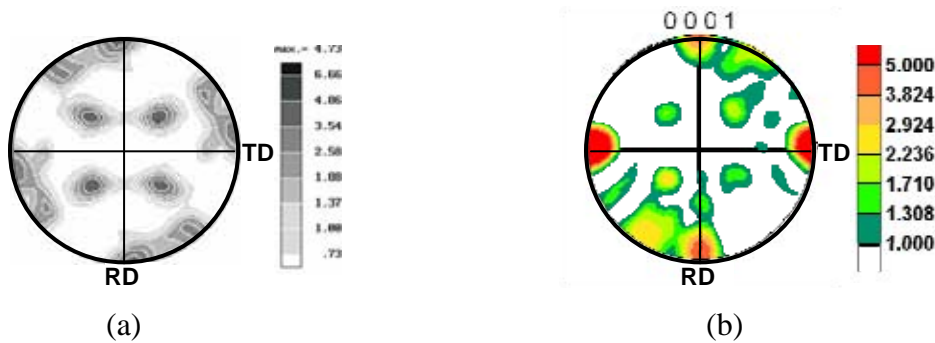


Figure 7. (a) Beta-phase ( $\beta$ ) {110} pole figure determined by XRD technique and (b) the secondary alpha-phase ( $\alpha_s$ ) {0001} pole figure determined by EBSD/EDS for Ti 6Al-4V after hot rolling at 955°C with 3 min reheat.



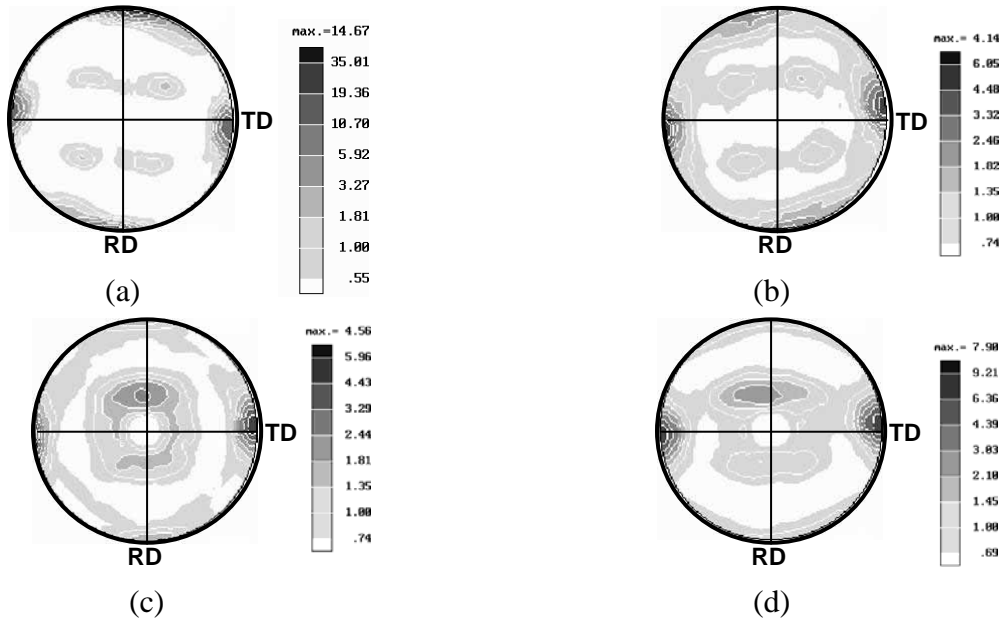


Figure 8. Alpha-phase ( $\alpha_p + \alpha_s$ ) {0001} pole figures determined by XRD for Ti-6Al-4V (a) as heat treated and furnace cooled, (b) rolled at 955°C with 3 min reheat, (c) rolled at 955°C without reheat, and (d) rolled at 815°C with 3 min reheat

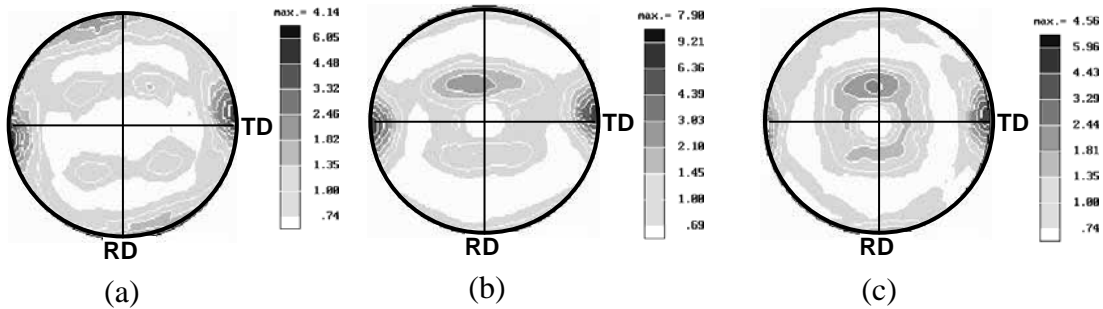


Figure 9. Primary Alpha-phase ( $\alpha_p$ ) {0001} pole figures determined by XRD for Ti 6Al-4V (a) rolled at 955°C with 3 min reheat, (b) rolled at 955°C without reheat, and (c) rolled at 815°C with 3 min reheat.

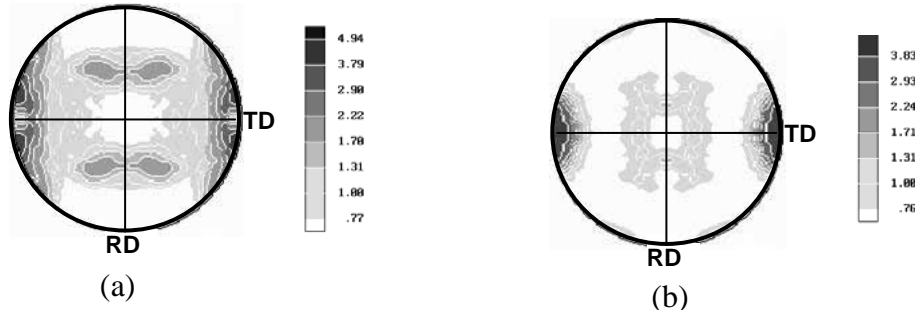


Figure 10. Secondary alpha-phase ( $\alpha_s$ ) {0001} pole figures determined by texture subtraction technique [??] for Ti 6Al-4V (a) rolled at 955°C with 3 min reheat and (b) rolled at 955°C without reheat. Note, that the material rolled at 815°C with reheat did not have secondary alpha (figure 3c).